

Development of a Real Time Internal Charging Tool for Geosynchronous Orbit

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The high-energy electron fluxes encountered by satellites in geosynchronous orbit pose a serious threat to onboard instrumentation and other circuitry. A substantial build-up of charge within a satellite's insulators can lead to electric fields in excess of the breakdown strength, which can result in destructive electrostatic discharges. The software tool we've developed uses data on the plasma environment taken from NOAA's GOES-13 satellite to track the resulting electric field strength within a material of arbitrary depth and conductivity and allows us to monitor the risk of material failure in real time. The tool also utilizes a transport algorithm to simulate the effects of shielding on the dielectric. Data on the plasma environment and the resulting electric fields are logged to allow for playback at a variable frame rate.

Nomenclature

E	= electric field (V/m) OR particle energy (MeV)
Φ	= electric potential (V)
ρ	= charge density (C/m ³)
κ	= dielectric constant
ϵ_0	= permittivity of free space (F/m)
J_R	= radiation current density (A/m ²)
J_C	= conduction current density (A/m ²)
σ	= conductivity (S/m) OR surface charge density (C/m ²)
σ_{dark}	= conductivity in the absence of radiation (S/m)
k_p	= radiation dose coefficient
$\frac{d\gamma}{dt}$	= radiation dose rate (# particles-s ⁻¹)
x	= depth (m)
η	= number transmission coefficient of electrons
R_{ex}	= extrapolated range (m)
Z	= atomic number

I. Introduction

Spacecraft charging and its effects on internal systems have been of great interest to the space physics community for the past several decades. Electrostatic Discharge (ESD) arcing as a result of charging has led to dozens of documented anomalies in satellite electrical subsystems, which have spurred efforts for a more detailed understanding of this phenomenon. Of particular interest is the process of internal charging, in which high-energy electrons (in the MeV range) penetrate an insulator or other dielectric material and deposit their charge and energy. The accumulation of charge at depth due to the high energy fluxes encountered in geosynchronous orbits can lead to electric fields in excess of the breakdown strength, creating a serious risk of failure within dielectric materials.

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This paper details the development of the Real Time Geosynchronous Internal Charging Tool, software which provides continuously updated data on the electric field intensity along a depth profile for a dielectric material across a wide range of conductivities. The tool receives real time input on the plasma and radiation environment from the National Oceanic and Atmospheric Administration’s (NOAA) Geostationary Operational Environmental Satellite 13 (GOES-13), a weather satellite currently orbiting at a longitude of 75° west. The tool processes this data to form complete electron flux energy spectra. This environmental data is used as input for a modified version of the NUMIT (for “numerical integration”) internal charging simulation tool, an existing model which remains widely used within the U.S. aerospace community. To simulate the effects of shielding, the tool utilizes an empirically derived transport algorithm developed by Tabata and colleagues⁵. Finally, the tool automatically logs data on the resultant electric field conditions, which can be plotted in real time or played back at an accelerated frame rate.

Section II details the analytical models used by the tool for the computation of the electric field within the dielectric, the deposition of energy from the incident electron current, and the current and energy losses due to shielding. Part E of Section II explains the computation of a complete electron flux energy spectrum from the GOES-13 data.

Section III explains the content and form of the tool’s output and describes its basic functionality.

Section IV provides brief insight into the ways in which this tool might be implemented or further enhanced for future applications.

II. Internal Charging Physics and Models

A. Internal Charging Physics

What follows is an overview of the internal charging model on which the NUMIT tool is based. For a more thorough derivation of this model, see Ref. 4. The interaction of injected electrons with molecules in the insulator, while intrinsically a microscopic phenomenon, can be reasonably modeled using bulk charging equations by introducing the concept of radiation-induced conductivity (RIC)⁴. This RIC value has both temporal and spatial dependence and is derived from the radiation dose rate throughout the material’s depth profile. From this macroscopic interpretation of charge transport, the electric field at any depth within the material can be succinctly given by the Poisson equation and the continuity of charge as follows:

$$\nabla \cdot \mathbf{E} = -\nabla^2 \Phi = \frac{\rho}{\kappa \epsilon_0} \quad (1)$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\mathbf{J}_R + \mathbf{J}_C) \quad (2)$$

where $\mathbf{E}$ gives the electric field, Φ the electric potential, ρ the charge density, $\mathbf{J}_R$ the radiation (electron) current density, $\mathbf{J}_C$ the conduction current density, κ the dielectric constant, and ϵ_0 the permittivity of free space. Due to the relatively negligible penetrating power of ions in the plasma environment, only electron currents are considered for the purposes of the model. From Ohm’s Law, we have that the conduction current $\mathbf{J}_C$ will be given by

$$\mathbf{J}_C = \sigma \mathbf{E} = \left[\sigma_{\text{dark}} + k_p \left(\frac{d\gamma}{dt} \right)^\alpha \right] \mathbf{E} \quad (3)$$

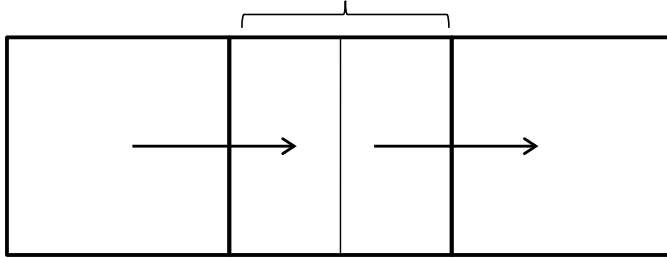
where σ_{dark} gives the intrinsic conductivity (in the absence of radiation) and $\frac{d\gamma}{dt}$ the radiation dose rate. The parameters k_p and α depend on the energy distribution of electron trapping states in the insulating material. These two parameters are difficult to determine without costly experimentation, so conservative estimates are often made for a range of substances.

B. NUMIT Internal Charging Model

The NUMIT code implemented in this tool applies the macroscopic model outlined in Section II. A, which solves the equations in one dimension through finite difference approximation for 150 discrete spatial steps within the insulating material. The dose rate depth profile is computed from the electron energy flux spectra using the EDEPOS transport code⁸, which is based on an algorithm derived from Monte Carlo simulations. The dose rate computed by this subroutine is used to compute the time-dependent RIC value at each discrete depth within the insulating material. The charge density at each step is then modified by the surrounding differential current densities, which are multiplied by a constant time step of 1 second:

$$\Delta\rho\Delta x = -(\Delta J_c + \Delta J_R)\Delta t \quad (4)$$

The updated charge density is then used to compute the resulting electric field using Gauss' Law, with the charge in each layer treated as a uniform distribution of infinite extent in the y-z plane.



$$\Delta J = (J_R + J_C)(x_1) - (J_R + J_C)(x_2)$$

$$\Delta J \Delta t = \Delta \rho \Delta x = \sigma$$

$$\nabla \cdot E = \frac{\rho}{\epsilon}$$

$$E(x_1) = -\frac{\sigma}{2\epsilon}$$

(5-8)

Figure 1. NUMIT one-dimensional Charging Model

While the depth of the material may be arbitrarily specified by the user, the NUMIT code as implemented always subdivides the insulator into 150 equally sized bins to ensure that computational runtime limits are not exceeded.

C. DEPOSI Radiation Model

The radiation current due to the electron flux was computed using the DEPOSI algorithm, a modified version of Tabata's algorithm⁸ which was modified to calculate fast electron currents as well as dose rates under electron irradiation. For a more thorough outline of the algorithm, see Ref. 8. The algorithm was derived from a simple model originally developed by Kobetich and Katz² given by

$$D(x) = -\frac{d\{E(x)\eta(x)\}}{dx} \quad (9)$$

where D gives the absorbed dose per unit fluence at the depth x, E the average energy of transmitted electrons, and η the number transmission coefficient of electrons. The average energy is expressed by the following relation:

$$E(x) = E_0 \exp(-a_1 s - a_2 s^{1+a_3}) \quad (10)$$

where E_0 gives the initial kinetic energy of the electrons, while the parameters a_{1-3} depend on both the incident energy E_0 and the atomic number of the insulator Z. Here, s represents the ratio of the depth x to the so-called extrapolated range R_{ex} , a value which is given by a semi-empirical formula⁷. The number transmission coefficient of electrons is given by

$$\eta(x) = \exp(-\alpha s^\beta) \quad (11)$$

where

$$\alpha = \left(1 - \frac{1}{\beta}\right)^{1-\beta} \quad (12)$$

with β a parameter also dependent on E_0 and Z. As per the original model of Kobetich and Katz, the effects of backscattering of incident electrons and the transport of energy by bremsstrahlung photons are neglected, but these effects are approximated by way of a normalization factor f given by

$$f = 1 - f_b - f_r \quad (13)$$

where f_b and f_r give the average fractions of incident energies backscattered from the incident surface and of the incident energy deposited via radiative processes at the depths corresponding to the bremsstrahlung tail, respectively. Thus, the final form of Eq. 9 is given by

$$D(x) = (fE_0/r_{ex})\{a_1 + a_2(1 + a_3)s^{a_3} + \alpha\beta s^{\beta-1}\}\exp(-a_1 s - a_2 s^{1+a_3} - \alpha s^\beta) \quad (14)$$

For details on the empirical determination of the above parameters, please consult Ref. 8.

D. Shielding Algorithm

The tool utilizes a simple transport algorithm to simulate the effects of shielding on the incoming flux. This algorithm was taken from Ref. 1, while the treatment of analytic fits was pulled from Ref. 5. Due to the nature of the flux data received from the NOAA GOES-13 satellite, all electrons are assumed to be at normal incidence to the surface of the shield. The formula for the extrapolated range is given as

$$R_{ex} = \frac{0.2335A_W}{Z^{1.209}} \left[\frac{\ln(1+1.78 \cdot 10^{-4} Z T)}{1.78 \cdot 10^{-4} Z} - \frac{(0.9891-3.01 \cdot 10^{-4} Z) T}{1+(1.468-1.18 \cdot 10^{-2} Z) T^{1.232/Z^{0.109}}} \right] \quad (15)$$

where A_W gives the atomic weight, Z the atomic number, and T the ratio of the electron's energy to its rest energy. The average energy of an electron transmitted through a shield of thickness d is given by Ref. 8:

$$E_{trans} = T_0 \exp(-D(b_1 + b_2 D^{b_3})) \quad (16)$$

where D is given as the ratio of the shielding thickness to the extrapolated range, R_{ex} :

$$D = \frac{d}{R_{ex}} \quad (17)$$

while b_{1-3} are parameters with dependence on both the incident energy E_0 and the atomic number Z . In addition to depositing energy in the shielding, a mono-energetic beam of electrons will also deposit a fraction of its charge. This loss of current is expressed through a transmission coefficient given as

$$CURR = \frac{1+e^{-s}}{1+e^{(s+2)D-s}} \quad (18)$$

where s is a parameter dependent on the incident energy E_0 . For the purposes of the real time charging tool, the electron energy flux spectra was subdivided into 100,000 bins corresponding to mono-energetic electron beams. Each bin was then downshifted in energy and current density as per the algorithm above and then reorganized into spectra readable by the NUMIT charging model.

E. Electron Flux Environment Model

The primary input to the real time charging model is the electron flux spectra, the distribution of electron flux with respect to energy which is incident on the GOES-13's detectors. Data taken by the GOES-13 satellite on the electron flux is provided by NOAA in the form of five minute time-averaged fluxes (in units of # $e^-/\text{cm}^2\text{-s-sr}$) for two specified energy thresholds: the flux of electrons with energies in excess of 0.8 MeV, and the flux of electrons in excess of 2.0 MeV.

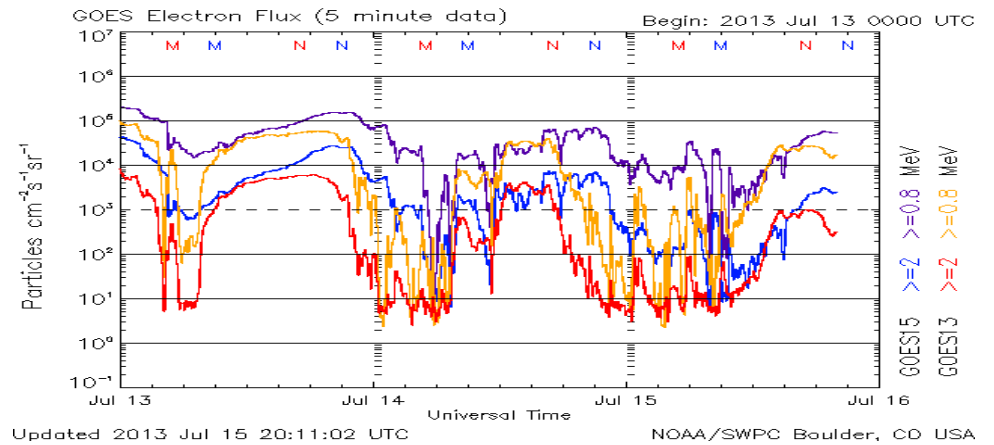


Figure 2. Data from the GOES-13 satellite

To complete the electron flux spectra for use in the charging model, we assume a power law distribution of electron flux density with respect to energy. The density function is given as

$$f(E) = CE^k \quad (19)$$

where the flux of particles in excess of an energy E_1 is given by

$$J(E > E_1) = \int_{E_1}^{\infty} f(E) dE \quad (20)$$

The two parameters C and k are determined from the simple system of equations we receive by applying this distribution to the observed fluxes as follows:

$$J(E > 0.8 \text{ MeV}) = \int_{0.8}^{\infty} CE^k dE \quad (21)$$

$$J(E > 2.0 \text{ MeV}) = \int_{2.0}^{\infty} CE^k dE \quad (22)$$

With these two parameters, the environment model calculates the electron flux for eighteen specified energy bins which span from .05 MeV to 25.8 MeV. For example, the flux of particles with energies between E_1 and E_2 is given as

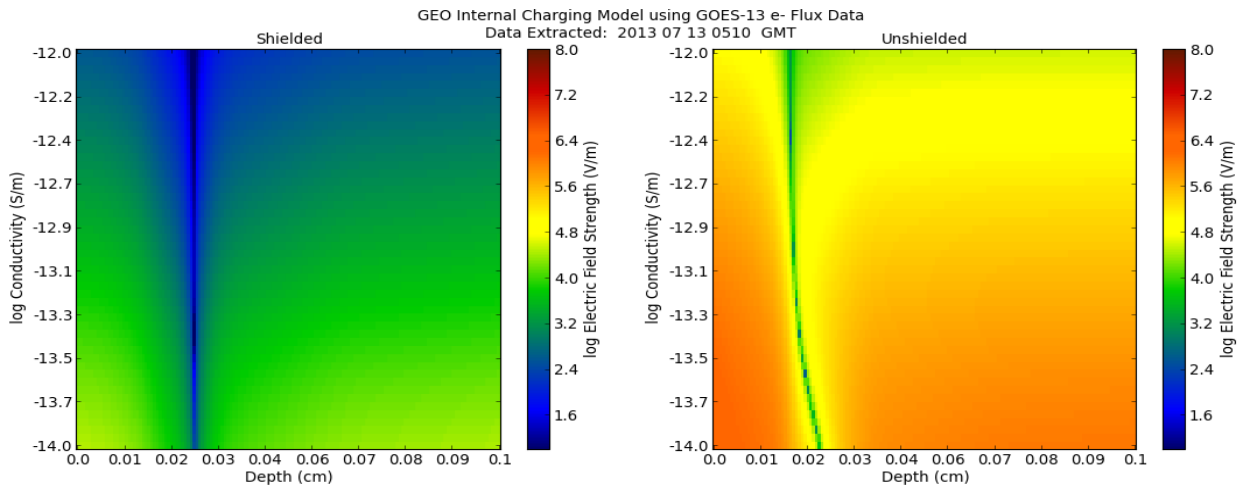
$$J(E_1 < E < E_2) = \int_{E_1}^{E_2} CE^k dE \quad (23)$$

The flux of each of these 18 bins is then assigned to a mono-energetic beam whose energy is given as the weighted average of the bin's energies.

III. Output

A. Format

The charging model is designed to run continuously, extracting data on a five-minute loop. For each set of electron flux values taken from GOES-13, the charging model outlined in part II runs through 50 complete iterations, each with a different value for the insulator's dark conductivity, σ_{dark} . These values are taken at equal intervals on a logarithmic scale, the bounds of which are specified by the user. The results from these 50 iterations are displayed in a 2-dimensional color plot, where the depth is given in cm on the x-axis, the log of the conductivity in S/m along the y-axis, and the log of the electric field strength in V/m by the color. In the case that shielding was applied to the insulator, the tool provides side-by-side outputs of these color plots, with the left plot corresponding to the shielded insulator and the right plot giving the unshielded insulator for the purpose of comparison.



(a) Shielded with $6.90\text{E-}2 \text{ g/cm}^2$ of Al

(b) Unshielded

Figure 3. Output from the real time charging tool.

Read from left to right at a specific y-value, the plot allows the user to view the electric field strength throughout the depth of the insulator of uniform conductivity. Read from top to bottom for a specific x-value, the plot shows the effect of varying conductivities on the electric field strength at a particular depth within an insulator under the same environmental conditions. The plot is color coded to roughly reflect the relative risk of breakdown within the dielectric, with a field strength of $10^1 - 10^4$ (represented by a gradient from blue to green) corresponding to safe or tolerable levels, while the range from $10^5 - 10^8$ (represented by a gradient from yellow to dark red) indicates a substantial risk of breakdown, depending of course upon the intrinsic electrical properties of the insulator.

B. Data Playback

While the real time charging tool outputs the color plots to the screen as they are updated by default, the tool also includes the option of playing back previous output at an accelerated frame rate. The tool incorporates a simple LINUX GUI which enables the user to specify a range of time for which data has been taken as well as the rate at which the data is to be displayed. The intent of course is to enable the user to study the effects of geomagnetic storms or other sorts of environmental events on the material in detail.

C. Time Series

The tool also creates twenty-four hour time plots of the maximum electric field strength measured over the entire depth profile for a specific conductivity. These plots allow the user to quickly scan data for a given day in order to identify any events of interest.

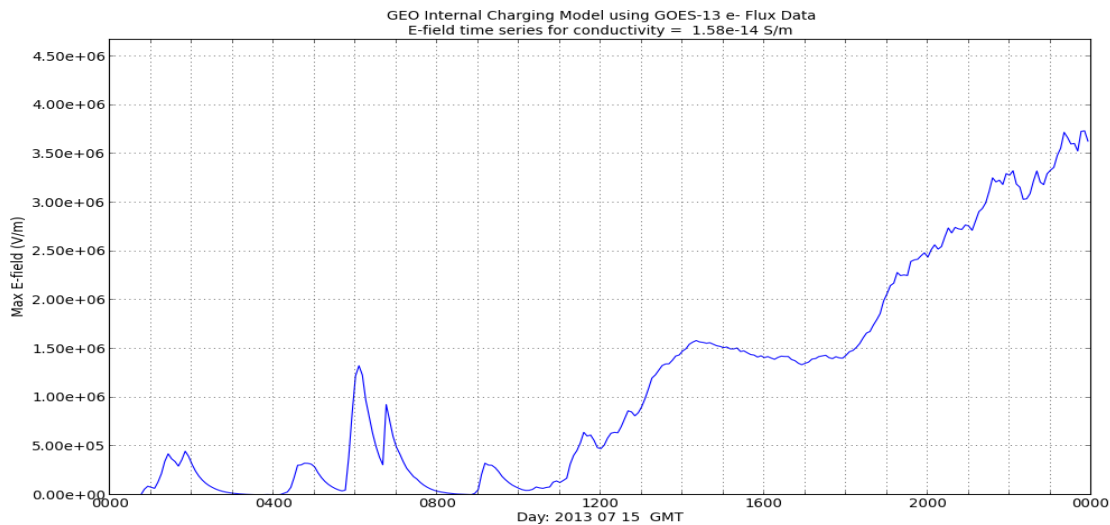


Figure 4. Time series of maximum electric field strength (V/m) vs. time (hhmm) for a conductivity of 1.58E-14 S/m

IV. Conclusion

This tool gives users a succinct way to visualize the charging effects of the real time plasma environment on satellites within geosynchronous orbit. The tool's universality allows it to be tailored to accommodate a wide range of geometries and design parameters. It can be easily modified to read historical data files for the study of past charging events, and its output can be coupled to any number of additional tools or models designed for the study of internal charging phenomena, including for example routines to model the effects of electrostatic discharge within an insulator coupled to a spacecraft's electrical subsystems. Such model development remains a vital part in refining the design of satellite and other spacecraft shielding to protect internal instrumentation and other critical systems in the most efficient manner possible.

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